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# Integration Between the Environmental Stress Index (ESI) and the Physiological Strain Index (PSI) as a Guideline for Training

LTC Daniel S. Moran, Ph.D.
Maj. Yuval Heled, M.Sc.
Heller Institute of Medical Research
Sheba Medical Center
Tel Hashomer 52621
Israel

Kent B. Pandolf, Ph.D, M.P.H.
Richard R. Gonzalez, Ph.D.
U.S. Army Research Institute of
Environmental Medicine
Natick, Massachusetts 01760-5007
United States of America

## Summary

A new environmental stress index (ESI), based on ambient temperature ($T_a$), relative humidity (RH) and global radiation (GR), was recently suggested as a potential substitute for the wet bulb globe temperature (WBGT) index. This new stress index, found to have a high correlation to WBGT, is constructed from fast reading meteorological response sensors ($T_a$, RH, and GR) that take only a few seconds to reach equilibrium. Furthermore, the ESI is the first stress index using direct measurements of solar radiation and is calculated as follows:

$$ESI=0.63T_a-0.03RH+0.002SR+0.0054(T_a \cdot RH)-0.073(0.1+SR)^{-1}$$

The recently suggested physiological strain index (PSI) is capable of indicating heat strain online and analyzing existing databases. The PSI is constructed from rectal temperature ($T_{re}$) and heart rate (HR) as follows:

$$PSI=5(T_{ret}-T_{re0}) \cdot (39.5-T_{re0})^{-1}+5(HR_t-HR_0) \cdot (180-HR_0)^{-1}$$

where $T_{re0}$ and $HR_0$ are the initial $T_{re}$ and HR, and $T_{ret}$ and $HR_t$ are simultaneous measurements taken at any time. The PSI is scaled from 0-10, whereby each variable $PSI_{HR}$ or $PSI_{Tre}$ which represent the cardiovascular and the thermoregulation systems respectively, can contribute up to 5 units to the overall strain assessment.

The purpose of this study was to develop guidelines based on ESI and PSI for work-rest cycles (WRC) during training. In order to integrate PSI and ESI, we decided to use only the $PSI_{HR}$ component, which represents the metabolic rate and the strain reflected by the cardiovascular system. Furthermore, $PSI_{HR}$ is easier to measure, is easier to implement and simplifies the integration with ESI. Concomitantly, it categorizes the strain between 0-5, the higher the value, the higher the strain.

## Introduction

Training schedules that include work-rest cycles are a function of two main variables. The first is the exercise intensity and the second is climatic conditions. A combination of these two variables at any "time point" determines the strain and the stress for an individual. Recently, Moran and colleagues (11) introduced a new physiological strain index (PSI) based upon the summation in equal weights of individual strains in core temperature ($T_c$) and heart rate (HR), representing the combined strains of thermoregulatory and cardiovascular systems. Each strain system was scaled between 0-5. The PSI is thus scaled 0-10, and can be used on-line or during data analysis. The PSI can be applied at any time, including rest or recovery periods, whenever $T_c$ and HR are measured (11). In a recent series of studies, PSI successfully evaluated the strains in different clothing ensembles and climatic conditions during heat stress, during different levels of hydration and exercise intensity, for gender during heat stress, and for different age groups during 10-days of acclimatization and acute exercise heat-stress (6, 10, 11). Furthermore, this index, when adjusted for animal values, successfully rated and correctly discriminated between trained and acclimated rats exposed to exercise-heat stress. (5)

The combination of different climates, impermeable garments, and hydration levels during different exercise intensities is a challenge for assessment of the individual physiological strain. However, in two recent studies (6, 11), when different heat strain indices were applied to various independent databases, the other indices were limited in their ability to quantify the heat strain, whereas PSI was successful at all levels of heat exposure. PSI differs from previous indices. It is easier to interpret and use than other indicess available, and includes the ability to assess rest and recovery periods. PSI overcomes the shortcomings of previously described indices and can be used over a wide range of conditions.

Heat stress evaluation is generally determined through meteorological parameters that enable the estimation of the influence of several environmental factors on thermal comfort and physiological ability. The variables included in heat stress indices and their relative weights have changed over the years. In 1957, Yaglou and Minard (14) introduced the Wet Bulb Globe Temperature (WBGT) index, which gained popularity mainly due to its simplicity and convenience of use. This index is obtained mainly from three parameters: black globe temperature $(T_g)$ which reflects the solar radiation, wet bulb temperature $(T_w)$, and dry bulb temperature $(T_a)$. This index is calculated as follows:

$$WBGT = 0.7T_w + 0.2T_g + 0.1T_a$$

As noted before, the index has gained immense popularity over the years. The WBGT is in use in the field by the US Army and is the index from which training safety orders are based (3). It has been adapted by the World Health Organization (WHO) and the American College of Sports Medicine (ACSM) (1). In 1972, the National Institute for Occupational Safety and Health (NIOSH) set it as the criterion for occupational exposure to a hot environment (12). In 1982, it was approved by the ISO organization as an international standard for heat load assessment. Later on, work-rest regime regulations were made based on this index. However, WBGT was found to be limited in evaluating heat stress due to the inconvenience of measuring $T_g$ (7). It is important to note the correlation of this index to physiological responses was only partially tested and was based mainly on the correlation between the number of heatstroke cases during army training and the heat load as calculated by the WBGT (14).

In 2001, Moran et al. (9) introduced a new environmental stress index (ESI) based on measuerements of $T_a$, relative humidity (RH), and solar radiaton (SR) as follows:

$$ESI = 0.63T_a - 0.03RH + 0.002SR + 0.0054 (T_a \cdot RH) - 0.073(0.1 + SR)^{-1}$$

This newly developed index was validated by using large databases and was found to be highly correlated to the WBGT index (9).

ESI differs from other indices that have been suggested in the past for two main reasons. First, ESI is based on SR and RH, aside from using $T_a$. In fact, there are indices based on indirect measurements of SR and RH. For example, the WBGT uses $T_g$ for evaluating SR, and $T_w$ is used for estimation of RH. However, the ESI as a stress index, for the first time uses direct measurements of SR and RH. Second, the three meteorological variables used in ESI are characterized by fast reading responses and take only a few seconds to reach equilibrium. Recently, the ESI was validated with measurements from an infra-red (IR) light sensor for global radiation. It was concluded in that study that an IR light sensor can be used as a potential substitute for $T_g$ which is incorporated in the WBGT (8).

The purpose of this study was to develop easy-to-use guidelines for work-rest cycles during training based on the integration of PSI and ESI. Using these guidelines for different combinations of different levels of exercise intensity and environmental load should help in preventing heat casualties.

**Methods**

The primary index for physiological assessment used in this study is the PSI (11). However, in this study we only used the $PSI_{HR}$ component as follows:

$$PSI_{HR} = 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1}$$

As a consequence, $PSI_{HR}$ assessment ranged from 0-5, the higher the value, the higher the strain.

The newly developed ESI defined in this study uses the same heat categories and color-coded assessment as the WBGT index. Even though ESI is constructed from different variables than the WBGT, the outcome values are the same for both indices, including the heat category assessment of 1-5.

The length of work-rest cycles (WRC) at different WBGT conditions during training was estimated from the Montain et al. (4) study. The WRC were set from predicted core temperature and other physiological responses to work in the heat (13), and were set for preventing $T_c$ from rising above 38.5°C during 4 hours of sustained training. These values are the outcome of the predictive models for healthy, euhydrated and reasonbly fit soldiers.

Maximal HR ($HR_{max}$) was calculated as suggested by the American College of Sports Medicine Guidelines as follows (2): $HR_{max}$ = 220-age. Accordingly for each $PSI_{HR}$ assessment, the matched HR range was calculated.

## Results

Since PSI is constructed from $T_{re}$ and HR, each of these individual parameters can contribute different weight to the index, but up to a maximum of 5 units. However, when $T_{re}$ measurement is not possible or convenient to use, we suggest as an optional alternative using only $PSI_{HR}$ for strain assessment. The $PSI_{HR}$ ranges from 0-5, stands for the cardiovascular load and represents the metabolic state and strain by HR in minimal response time. For applicable usage of $PSI_{HR}$ for different individuals at different physical fitness, we add for each strain level the matched range of HR values (Table 1). These HR values are derived from calculated $HR_{max}$ for persons of 20 and 40 yrs ($HR_{max}$ of 180 and 200 beats/min, respectively) at low and moderate physical fitness.

**Table 1: Strain categorization by the heart rate component of the physiological strain index ($PSI_{HR}$) and the expected HR range for each strain category.**

| Strain | $PSI_{HR}$ | HR (beats/min) |
|---|---|---|
| No/Little | 0-1 | <95 |
| Low | 2 (Green) | 96-120 |
| Moderate | 3 (Yellow) | 121-145 |
| High | 4 (Red) | 146-170 |
| Very high | 5 (Black) | >171 |

Using the same WBGT assessment and based on Montain et al. (4) guidelines for work-rest cycles (WRC), we constructed a matrix, which, according to the heat stress (ESI), recommends WRC the for different exercise intensities depicted by $PSI_{HR}$ (Figure 1). The strain assessment by $PSI_{HR}$ uses the same color-coded categorization as the WBGT index.

| ESI | $T_a$ (°F) WRC (min) | $PSI_{HR}$ | | | |
|---|---|---|---|---|---|
| | | 50/10 | 40/20 | 30/30 | 20/40 |
| 1 | 78-81.9 | <4.5 | <4.5 | <4.5 | <4.5 |
| 2 (Green) | 82-84.9 | <4 | <4.5 | <4.5 | <4.5 |
| 3 (Yellow) | 85-87.9 | <3 | <4 | <4.5 | <4.5 |
| 4 (Red) | 88-89.9 | <2 | <3 | <4 | <4.5 |
| 5 (Black) | >90 | <1 | <2 | <3 | <4 |

**Figure 1: Recommended time (min) for work-rest cycles at different heat categories assessed by the environmental stress index (ESI) and by the heart rate component of the physiological strain index ($PSI_{HR}$).**

According to the heat category calculated by ESI and the requested strain assessed by $PSI_{HR}$, we can locate the correct cell in the matrix depicted in Fig.1, which recommends the work-rest cycles. The numbers (1-4.5) in the color-coded matrix represent the allowed strain according to the ESI and the WRC (e.g., for ESI=3 and WRC=50/10, exercise intensity of $PSI_{HR}$<3 is allowed, where according to Table 1, HR=121-145 beats/min).

These findings suggest simple guidelines for different strains at different levels of environmental stress. However, further evaluation is required to possibly adjust this matrix for different age groups, clothing and women.

## Discussion

In this study, we integrate between two new indices for strain and stress assessment into an easy-to-use visualized table. The integration between these two indices can serve as a guideline that should be easy to interpret and to implement for soldiers during training in order to prevent heat casualties.

The shortcoming of this work is the strain evaluation by $PSI_{HR}$. In our previous works, we emphasize the importance of strain evaluation by the cardiovascular and the thermoregulation systems presented by $T_c$ and HR, whereas in this study we only use $PSI_{HR}$ for strain assessment. We still believe that for more accurate strain assessment we should use PSI. However, under various circumstances and in some scenarios, $T_c$ measurement is not practical or convenient. Therefore, only HR measurement that immediately represents the metabolic rate and the strain reflected by the cardiovascular system can be used for strain assessment. In addition, HR is easier to measure, is easier to implement and it can be measured by the individual himself. Since the purpose of this work is to develop guidelines for work-rest cycles in order to help in preventing heat casualties from excessive heat, we should expect a practical and easy-to-use guideline. We believe that the $PSI_{HR}$ component can serve as a suitable alternative for PSI in circumstances where $T_c$ measurement cannot be taken.

The suggested matrix based on $PSI_{HR}$ and ESI is an attempt to give the decision maker an easy tool to use as a guideline. However, since this is the first study regarding the integration of PSI and ESI,

further studies should be made which consider different levels of physical fitness, types of clothing, hydration status, and acclimatization. In addition, it is expected to implement the suggested matrix for fluid replacement quantities.

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## Disclaimer

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